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EFFECT OF AGING ON MECHANICAL PROPERTIES OF ALUMINUM-ALLOY RIVETS

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SUMMARY

Curves and tabular data present the results of strength tests made during and after 2½ years of aging on rivets and rivet wire of 3/16-inch nominal diameter. The specimens were of aluminum alloy: 24S, 17S, and A17S of the duralumin type and 53S of the magnesium-silicide type.

For each of the four alloys tested, the ratio of shearing strength to tensile strength of the undeformed wire remained constant independent of aging time at room temperature. The aging times at room temperature required for undeformed wire to reach practically its final value of strength were: 24S, 7 hours; 17S, 3 days; A17S, 8 months; 53S, more than 2½ years. The aging times at room temperature required for rivets driven before aging to reach practically their final strengths were: 24S, 3 months; 17S, 1½ years; A17S and 53S, more than 2½ years. For a given total aging time after quenching, rivets driven after aging were always stronger than those driven before. The final values of driving stress for A17S and 53S rivets were reached after about 6 months and 1½ years, respectively. The final driving stress for A17S–T rivets was slightly higher than that required for 17S rivets immediately after quenching. The high driving stress required for a standard cone-point head on a 24S rivet driven immediately after quenching resulted in frequent crack formation.

Precipitation heat treatment of alloy 53S had to be carried out immediately after quenching to obtain the highest possible strength values. The strength of a 53S–T rivet after precipitation heat treatment was about the same as that of a 17S rivet immediately after quenching or of a freshly driven A17S rivet driven after 1 day of aging.

INTRODUCTION

In aluminum alloys, mechanical properties suitable for aircraft structural purposes are produced by heat treatment consisting in (a) heating to a definite temperature and then quenching (solution heat treatment) and (b) aging (see reference 1, pp. 67–73; reference 2; reference 3, pp. 101–6). Immediately after quenching, these materials are less strong and more readily workable than after aging. For some alloys aging occurs at room temperature but others require reheating at an elevated temperature (artificial aging, or precipitation heat treatment) to be fully hardened. The rate of age-hardening depends on the alloy, the aging temperature, and the amount of cold work, if any, done on the material after solution heat treatment. The change of any property of an alloy during aging may be described by an aging curve, in which the numerical values of the property are plotted against aging time (time after quenching).

The changes of mechanical properties during aging are a determining factor in the technique of cold riveting of aluminum-alloy materials. The cold work involved in the riveting process affects, in turn, the aging curves. Consequently, information on the interrelated effects of riveting and aging is of value to the aircraft manufacturer.

Data on certain aging curves have been obtained as part of a research program for the National Advisory Committee for Aeronautics on aluminum-alloy rivets conducted at the National Bureau of Standards. These data are presented in this paper. The cooperation of the Aluminum Company of America in donating the material used in this investigation is acknowledged.

The theoretical basis of heat treatment is of secondary interest in this paper. Clarification of the theory has, however, been the object of most investigators who have obtained data pertaining to aging curves of mechanical properties. These investigations have satisfactorily established the part played by solution heat treatment of aluminum alloys, namely, the production of a supersaturated solution of intermetallic compounds in aluminum. They have also brought forth several proposed explanations of the aging process in terms of the mechanism of constitutional changes within the metal. None of these has found general acceptance. Reference 1 and references 3 to 13, with their accompanying bibliographies, give an adequate representation of these investigations.

Aluminum alloys used for high-strength rivets have chemical compositions of either the duralumin type or the magnesium-silicide type. The duralumin type is alloyed with copper and magnesium, and usually manganese, and contains iron and silicon as impurities. The magnesium-silicide alloy most commonly used for rivets contains magnesium, silicon, and chromium, and also iron as an impurity. Duralumin-type alloys are aged at room temperature; aging of magnesium-silicide alloys is more effective at higher temperatures than at room temperature.

Another classification of rivet alloys, according to their workability, is also significant. The stronger alloys must be driven immediately after solution heat treatment to avoid danger of cracking; the more workable alloys may be driven cold in any condition. Magnesium-silicide alloys belong to the workable class; duralumin-type alloys are of both classes.

The stronger rivets age faster than the more workable ones. Their advantages, however, do not always compensate for the expense and the inconvenience of heat treatment of each batch of rivets immediately before driving. Two practical problems for which aging curves are useful arise in deciding which class of rivets to use: first, the requisite length of time for aging that must elapse after solution heat treating rivets before the structure is ready for use; and second, the permissible period of time after solution heat treatment within which rivets may still be driven.

The use of aging curves in dealing with the first problem involves determining the strength that the rivets will attain before they are loaded in service. This value may be termed the "eventual strength." Since, for properly heat-treated rivets, the aging curve presumably never drops off no matter how long the aging is prolonged, the eventual strength is higher the longer the time before the rivets are loaded. Of course, the rivets continue to age after being placed in service, but the subsequent increase in strength cannot be relied upon to resist the initial loading of the structure and so cannot properly be considered part of the eventual strength. In this paper the eventual strength values are those attained after about 2½ years of aging. In practice, the increase in eventual strength after an aging period of a few weeks is no longer sufficient to justify the additional delay in putting a structure into service.

In connection with the second of these problems, if the more workable rivets are used, the force required to drive them and their eventual strength depend on the aging time before driving. If the stronger rivets are used, aging curves give an indication of the limitation on the time between quenching and driving.

This period of time may be prolonged indefinitely by storage at sufficiently low temperatures. (See references 14 to 18, with accompanying bibliographies.) Resoftening at temperatures above room temperature, without complete reheat treatment (reference 19), has also been proposed as a substitute for repeated quenching. These matters are not within the scope of this paper.

The aging curves given in this paper present information pertinent to these two problems.

MATERIALS AND METHODS

ALLOYS INVESTIGATED

Data are presented concerning four aluminum rivet alloys, three of the duralumin type, and one of the magnesium-silicide type. The alloys are listed in table I, and the results of chemical analysis of samples of the wire from which the rivets used in this investigation were fabricated are given in table II. The materials complied with the requirements for chemical composition and mechanical properties in Navy Department Specification 43R5d.

HEAT TREATMENT

The solution heat treatment (table I and reference 20) was performed in an electrically heated salt bath. Recommended practice for solution heat treatment as set forth in Navy Department Bureau of Aeronautics Process Specification SR-53a (for duralumin-type alloys), and Bureau of Construction and Repair General Specifications, appendix 4, part II, sections 1 and 8 (for 53S alloy rivets) was followed in all details not specifically mentioned.

TABLE I.—RIVET ALLOYS INCLUDED IN THIS INVESTIGATION

Alloy designation	Composition type	Grade (Navy Dept. Specification 43R5d)	Normal driving condition	Solution heat-treatment temperature
24S	Al-Cu-Mg (1.5%)-Mn	D	As quenched	920°±10° F.
17S	Al-Cu-Mg-Mn	C	do	940°±10° F.
A17S	Al-Cu-Mg	F	Aged	940°±10° F.
53S	Al-Mg-Si-Cr	E	Aged (or precipitation heat-treated).	970°±10° F.

TABLE II.—CHEMICAL COMPOSITION OF RIVETS

Alloy designation	Chemical composition (percent)					
	Cu	Mg	Mn	Si	Cr	Fe
24S	4.5	1.4	0.62	0.17	----	0.27
17S	4.1	.49	.52	.27	----	.60
A17S	2.4	.29	<.01	.38	----	.40
53S	.03	1.2	<.01	.66	0.23	.22

During the solution heat treatment of any one batch of material, the furnace was continuously attended. No mechanical agitation of the bath was provided. In order to reduce the scatter in the aging curves due to slight variations in heat-treatment technique, specimens that provided data for one aging curve were, for the most part, solution heat treated together.

Specimens were quenched in tap water, which was changed occasionally but was not agitated nor circulated. Each piece was quenched individually within a few seconds after removal from the salt bath.

Precipitation heat treatment was carried out on some of the 53S alloy specimens in an electrically heated air oven maintained by thermostatic control at a temperature of 315° ± 5° F. for a heating period of about 18 hours. After removal from the oven, the specimens were cooled in air.

Room-temperature aging took place in a laboratory in which no temperature control was operative except for ordinary steam heat during the winter months. The temperature varied normally from 55° to 95° F. and may have fallen as low as 35° F. during some winter week ends. It was felt that the scatter resulting from these nonuniform aging temperatures should not be eliminated by constant-temperature storage because the variable "room temperature" corresponds more closely to conditions obtained in practice than would the controlled constant temperatures.

The fully aged condition of any alloy (including 53S after precipitation heat treatment) is denoted by the suffix T after the alloy designation. The condition of alloy 53S when aged at room temperature but not given precipitation heat treatment is designated 53S–W.

SPECIMENS

All specimens of both rivets and rivet wire were of 3/16-inch nominal diameter. Rivets had button manufactured heads (type 6, fig. 2, Navy Specification 43R5d, which is the same as type B–1, fig. 1, Bur. C. & R. Gen. Specs., appendix 4, pt. II) and were driven with cone-point driven heads (fig. 8, Bur. C. & R. Gen. Specs., appendix 4, pt. II). Riveted specimens for shearing-strength determinations consisted of single-rivet, single-shearing joints made of two sheets of alloy 17S–T. The sheets were 1/8 inch thick by 1 1/2 inches wide and were overlapped 1 1/2 inches with the rivet hole at the center of the overlap. Rivet holes were subdrilled and reamed to a diameter of 0.1935 inch, resulting in an upsetting of the rivet shank of 3.2 percent during driving. Riveting was done by the squeeze method, using the jig described in reference 21 (sec. IV, 3, and fig. 3).

Driving stress is defined as the quotient of the compressive force required to form the driven head of a rivet by "cold squeezing" divided by the nominal area of the (undriven) rivet. The driving stresses for shearing-strength specimens were determined by trial so as to produce driven heads approximately 9/32 inch in diameter. The length of shanks was 9/32 inch, giving a head allowance of 1.5 shank diameters and resulting in driven heads slightly deeper than standard, when driven to 9/32 inch diameter. (See fig. 8, reference 21.)

Rivet-wire specimens for tensile and shearing strength determinations were cut about 10 inches long. A length of approximately 2 inches was cut from the end of each sample after heat treatment for a double-shearing specimen; the 8-inch pieces were used for tensile specimens.

TESTING METHODS

Shearing-strength tests on riveted specimens were made with the fixtures illustrated in figure 16 of reference 21. The strength was computed by using the nominal cross-sectional area of the undeformed rivet, 0.02761 square inch.

Each rivet used for driving-stress determination was driven at three successive loads; the riveting technique and the thickness of sheets were the same as those used for shearing-strength specimens. The diameter of the driven head was measured with a vernier caliper after each increment of driving load. For each load the driving stress was plotted against values of the ratio of head diameter a to shank diameter d (3/16 in.). From each such curve through three points representing one specimen, the value of driving stress corresponding to $a/d=1.50$ was read off (standard value for cone-point heads).

Tensile tests of wire specimens were made in Templin grips, and the strength was computed by using the area obtained from diameter measurements made on each specimen before testing. Shearing tests of wire specimens were made in the special double-shearing fixture illustrated in figure 14 of reference 21. This fixture was adjusted to provide a clearance of 0.009 to 0.010 inch between each pair of hardened steel shearing edges and to shear out a segment 3/8 inch in length from the specimen, with practically no bending nor axial deformation. The strength was taken as the maximum load divided by twice the area of the wire.

All testing machines used in this investigation conformed to the requirements of A. S. T. M. Standard Methods of Verification of Testing Machines: E4–36.

The time at each operation was noted to the nearest minute for each specimen. The "aging time" used as abscissa in plotting results was the interval between quenching and testing.

PROGRAM AND RESULTS OF TESTS

ALLOYS 24S AND 17S

For alloys 24S and 17S, two series of rivet-wire specimens and one series of riveted-joint specimens were prepared, aged for various lengths of time, and tested. In the riveted specimens, all rivets were driven within 5 minutes after quenching. The values determined were the tensile strength and the shearing strength (double shear) of rivet wire, and the shearing strength of driven rivets (single shear). The results are shown in figures 1 to 6. Each point in these figures represents one specimen, except the last point (100 percent eventual strength) on each plot. The eventual strengths and the number of specimens used to determine them in each case are given in table III. Additional tensile tests were made on samples of rivet wire from the coils from which the rivets had been fabricated. These coils had been heat-treated before delivery to the laboratory and samples were tested as received. The results are given in table IV.

TABLE III.—EVENTUAL STRENGTHS OF ALLOYS 17S-T AND 24S-T

Alloy	Type of specimen	Type of test	Results shown in figure	Eventual strength (lb/sq in.)	Aging time for eventual strength (hr)	Number of specimens for eventual strength
24S-T	Rivet wire	Tensile	1	70,900	20,200	3
	do	Double shear	2	42,500	20,150	3
	Riveted joint	Single shear	3	46,900	20,050	1
17S-T	Rivet wire	Tensile	4	[a] 60,200	20,200	4
				[b] 58,600	21,700	1
	do	Double shear	5	[a] 38,100	20,150	4
				[b] 37,200	21,700	1
	Riveted joint	Single shear	6	38,700	20,050	1

[a] Coil A.
[b] Coil B.

TABLE IV.—TEST RESULTS ON WIRE FROM WHICH RIVETS WERE MADE

[These samples were tested as received. The aging time is computed from information furnished by the rivet manufacturer]

Alloy	Aging time (hr)	Tensile strength, T (lb/sq in.)	Shearing strength, S (lb/sq in.)	Yield strength (lb/sq in.)	Elongation in $4d$ (percent)	S/T
24S-T	410	72,200		46,300	24.8	
	29,300	72,000	43,400			0.60
17S-T	1,750	60,900		37,800	25.9	
	30,600	60,900	38,600			.63

Tests were also made to determine the driving stress required to produce a standard cone-point head (a/d=1.50) on a rivet driven within 5 minutes after quenching. The results gave a value of 168,000 pounds per square inch for 17S rivets and 216,000 pounds per square inch for 24S rivets.[1] It was found that, in many 24S rivets, cracks formed during driving before the a/d ratio reached 1.5.

The driving stresses used in preparing the riveted-joint shearing specimens were 150,000 and 200,000 pounds per square inch for 17S and 24S rivets, respectively. No data from specimens having cracks in the rivet heads are included in figure 3. No difficulty with cracks was experienced in driving 17S rivets.

ALLOYS A17S AND 53S

The program described in the preceding section was repeated for alloys A17S and 53S. In addition, rivets for two series of specimens for each alloy were given solution heat treatment. These rivets were driven after various aging times. One series for each alloy was tested immediately after driving for shearing strength; the other series was used to provide data for an aging curve of driving stress required to form a standard cone-point head. The results are shown in figures 7 to 16. The eventual strengths are given in table V. Results of tensile tests made on samples of the rivet wire from which the rivets had been fabricated are given in table VI.

A limited number of tests was made on 53S material subjected to precipitation heat treatment in order to throw light on the following problems: (1) the values of strength attained through the recommended precipitation heat treatment; (2) the driving stress required to form a standard cone-point head, after the recommended precipitation heat treatment; (3) the effect of room-temperature aging after precipitation heat treatment; (4) the effect of room-temperature aging between the solution and precipitation heat treatments; and (5) the effect of repeated solution heat treatment before and after precipitation heat treatment. The results of these tests are given in table VII. Each section of table VII is divided into three parts. The upper two parts of each section give, for comparison, strength values obtained immediately after quenching and after quenching and room temperature aging, respectively. The lower part of each section gives values obtained as a result of precipitation heat treatment. In no case were any rivets subjected to a heat treatment after driving. The exact sequences of operations for these specimens are indicated by the letter symbols in the first column of the table, with its accompanying footnotes.

TABLE V.—EVENTUAL STRENGTHS OF ALLOYS A17S-T AND 53S-W

Alloy	Type of specimen	Type of test	Results shown in figure	Eventual strength (lb/sq in.)	Aging time for eventual strength (hr)	Number of specimens for eventual strength
A17S-T	Rivet wire	Tensile	7	45,100	20,200	2
	do	Double shear	8	30,200	20,150	2
	Riveted joint	Single shear [1]	9	29,800	23,250	8
	do	Single shear [2]	10	35,350	21,650	2
	do	Driving stress [3]	11	176,000	20,150	3
53S-W	Rivet wire	Tensile	12	35,750	20,150	2
	do	Double shear	13	24,250	20,150	2
	Riveted joint	Single shear [1]	14	22,400	23,000	2
	do	Single shear [2]	15	26,400	23,100	2
	do	Driving stress [3]	16	128,500	23,100	2

[1] DBA, driven before aging.
[2] DAA, driven after aging.
[3] Values given are eventual values of driving stress required to form standard cone-point head.

TABLE VI.—TEST RESULTS ON WIRE FROM WHICH RIVETS WERE MADE

[These samples were tested as received. The aging time is computed from information furnished by the rivet manufacturer]

Alloy	Aging time (hr)	Tensile strength, T (lb/sq in.)	Shearing strength, S (lb/sq in.)	Yield strength (lb/sq in.)	Elongation in $4d$ (percent)	S/T
A17S-T	2,150	45,900		28,400	32.7	
A17S-T	31,000	47,050	31,900			0.68
53S-W	1,750	34,200		18,300	33.8	
53S-W	30,600	36,600	25,200			.69

[1] Head diameters produced by driving stresses different from these standard values are reported in reference 21, fig. 8, for 17S rivets of ¼-inch diameter. The tests show that the driving stress required to produce a given a/d ratio is not appreciably dependent on the diameter of the rivet. Furthermore, the driving stress required to produce a given a/d ratio is the same fraction of the standard driving stress, within limits of observational error, for any alloy driven immediately after quenching. For rivets driven after aging, the slope of the driving stress-head diameter curve is slightly steeper.

TABLE VII.—RESULTS OF TESTS ON 53S ALLOY

[All material was given an air-furnace solution heat treatment S by the manufacturer before delivery to the laboratory. In cases in which this treatment is believed to have affected the strength value, the parenthetical prefix (S) has been employed in the table]

Sequence of operations [1,2]	Wire			
	Tensile		Shearing	
	Number of specimens	Strength (lb/sq in.)	Number of specimens	Strength (lb/sq in.)
ST	[3] Minimum	22,150	[4] Minimum	15,600
SPST	2	22,400	----------	----------
(S)[a] PST	2	22,300	----------	----------
S[b]T	[3] Maximum	[5] 35,750	[4] Maximum	[5] 24,250
(S)[a]T	2	36,300	----------	----------
SP[e]T	10	43,600	8	28,000
(S)[a]P[e]T	2	37,400	----------	----------
SP[d]SP[e]T	15	43,500	15	26,100

Sequence of operations [1,2]	Riveted joints			
	Number of specimens	Shearing strength (lb/sq in.)	Number of specimens	[1] DS (lb/sq in.)
SCT	[6] Minimum	16,700	[7] Minimum	89,000
SPSCT	1	17,100	----------	----------
(S)[a]PSCT	1	17,000	----------	----------
S[b]CT	[6] Maximum	[5] 26,400	[7] Maximum	[5] 128,500
(S)[a]CT	1	25,000	----------	----------
SC[b]T	[6] Maximum	22,400	----------	----------
SP[c]CT	17	31,400	16	142,000
SPC[c]T	14	31,000	----------	----------
(S)[a]P[c]CT	4	28,200	----------	----------
SP[d]SP[c]CT	8	31,800	----------	----------
SP[d]SPC[e]T	14	31,300	----------	----------

[1] Symbols used for designations are defined: DS, driving stress required for standard cone-point head; S, solution heat treatment; P, precipitation heat treatment; C, driving the rivet; T, testing.

[2] The lapse of aging time between operations is denoted by superscript letters a to e: [a] greater than 22 weeks; [b] various intervals from 5 min to 2½ yr. (see figs. 12 to 16); [c] various intervals from 15 min. to 2½ yr; no significant trend with time is indicated by the data, [d] 1,110 hr. (approximately 6½ weeks), [e] 2,550 hr. (approximately 15 weeks). Where no superscript letters appear, the time between successive operations ranged as follows: S and T, 5 to 13 min; S and P, 5 to 25 min; P and S, 1 to 6 hr; S and C, 1 to 5 min; P and C, 10 min to 3½ hr; C and T, 2 to 50 min.

[3] Data taken from fig. 12.

[4] Data taken from fig. 13.

[5] Results of usual sequence of operations for producing 53S-W temper.

[6] Data taken from figs. 14 and 15.

[7] Data taken from fig. 16.

DISCUSSION AND COMPARISON OF RESULTS

GENERAL

The data show, in confirmation and extension of conclusions reached by Teed (reference 22, ch. IX) from data on a British alloy equivalent to 17S, that the aging curves for tensile strength and shearing strength of rivet wire for any one of the alloys are practically identical when plotted in terms of percentage of eventual strength. The time required to reach a final strength value (that is, the aging time beyond which further increments of strength are no larger than the scatter of data from like specimens), however, varies widely from alloy to alloy. This time for complete aging is less in the case of the wire tests than for riveted joints of the same alloy. This observation is in apparent contradiction to the conclusion drawn by several investigators that cold work immediately after quenching accelerates the age-hardening process while reducing its total effect. (See reference 11 and references 23 to 26; see also later discussion.) Burns (reference 27) reaches a conclusion in accord with the present data, although based on meager tests.

Smoothed curves representing the shearing strength of driven rivets for all the alloys are shown in figure 17. This figure provides direct numerical comparison of rivet strengths attained for the four alloys, under the various conditions of heat treatment, aging, and driving ordinarily employed. A similar comparison of driving stresses required for a standard cone-point head is afforded by the curves shown in figure 18.

Table VIII is a skeleton summary of the shearing strength data, giving directly comparable values for the strength of undeformed rivet wire and driven rivets. Account has been taken of the increased area resulting from driving rivets. The data for alloys A17S and 53S given in figure 17 indicate that rivets driven after aging are substantially stronger than rivets of the same alloy driven before aging. It appears from table VIII that this effect arises from a difference in the aging curves of deformed and undeformed material rather than from any considerable difference in the immediate effect of driving on the strength of aged and unaged rivets.

TABLE VIII.—SHEARING STRENGTHS OF DEFORMED MATERIAL (DRIVEN RIVETS) AND UNDEFORMED MATERIAL (RIVET WIRE), ADJUSTED [1] TO PROVIDE DIRECT COMPARISON

Alloy	100 percent shearing strength (lb/sq in.)	As quenched		Aged 4 days			Aged 2½ years		
		Undeformed (percent)	Deformed (percent)	Undeformed (percent)	Deformed before aging (percent)	Deformed after aging (percent)	Undeformed (percent)	Deformed before aging (percent)	Deformed after aging (percent)
24S	43,400	80	84	97	97	----	100	101	----
17S	38,600	73	73	100	86	----	100	94	----
A17S	31,600	64	67	92	80	99	100	89	105
53S	24,500	63	65	91	71	86	100	86	101

[1] Data for this table required adjustment to be directly comparable, because figs. 2, 5, 8, and 13 (wire data) represent different lots of material from fig. 17 (rivet data) and also because rivet strengths for fig. 17 were computed by using the nominal area of the undriven rivet rather than the actual area of the driven rivet.

ALLOY 24S

Wire specimens of alloy 24S attained more than 96 percent of their final strength within 7 hours aging time; driven rivets attained the same amount within 2 days. Thereafter a further period of slight strength increase occurred in the range from 3 weeks to 3 months aging time, after which no further increases were noted. The tensile-strength data are in excellent agreement with those presented by Hansen and Dreyer (reference 28) on an equivalent experimental German alloy. The effect of the rivet-driving deformation on the strength, immediately after quenching, was an increase of about 4 percent; the accompanying delay in aging of driven rivets was slight; the final values for driven rivets were higher than for undeformed wire by an insignificant amount.

ALLOY 17S

The aging of rivet wire of alloy 17S completed its entire course between 30 minutes and 3 days aging time. During the first half hour after quenching, the strength did not increase; this period has been called the incubation time. The research of Fraenkel and Hahn (reference 29) on a German alloy (duralumin 681–B) equivalent to 17S has shown that long incubation time can result from long heating before quenching, or from increased iron content, but the essential conditions for the occurrence of an incubation period remain undiscovered.

With regard to the strength immediately after quenching and the time required for complete aging, the data are in good agreement with results presented by Anderson (reference 30), Schmid and Wassermann (reference 31), Teed (reference 22, ch. IX), Hansen and Dreyer (reference 28), and Brenner and Kostron (reference 32) on alloys equivalent to 17S. None of these investigators present data adequate to define the incubation period. For aging times between 2 hours and 3 days, the data of figure 4 are in good agreement with the curves of Anderson, Hansen and Dreyer, and Brenner and Kostron; values reported in references 22 and 31 are lower by as much as 8 percent in this range. This discrepancy can be explained on the basis of differences in room temperature. Abraham (reference 16) presents data on material of German alloy duralumin 681–A with slightly lower copper content (3.4 percent) than 17S (3.5 to 4.5 percent) which was aged at various constant room temperatures. Von Zeerleder (reference 18) presents similar data on "Avional D" alloy in fair agreement with Abraham. An analysis of Avional in reference 33 shows it to be equivalent to 17S. The data of figure 4 (for which work on specimens aged a short time was carried out in the summer at temperatures of 75° to 95° F.) agree well with Abraham's data for an aging temperature of 82° F.; Teed's data, which were taken at temperatures of 55° to 65° F., agree well with Abraham's data for 59° F.

The final strength of 17S driven rivets was attained only after aging for at least 1½ years. The shearing strength immediately after quenching (table VIII) was the same for driven rivets as for undeformed wire, but since there was no incubation period for the driven rivets, they were stronger for aging times up to 2 hours than undeformed wire. The final strength of driven rivets was about 6 percent less than that of undeformed wire. For 2 weeks aging time, the strength of driven rivets was about 8 percent less than for undeformed wire. This result is in good agreement with the results (shown in fig. 15 of reference 21) from 17S wire that had been heat-treated, immediately upset, aged about 2 weeks, and tested.

The results stated in the preceding paragraph are in contradiction, in some respects, to conclusions, based on numerous data, that have been drawn by several investigators. (See reference 11 and references 23 to 26.) An explicit representative statement of these conclusions has been made by Teed (reference 22, p. 25, or reference 23) and discussed at length by Kostron (reference 26). The points of difference and possible explanations are:

1. Deformation is supposed to produce an instantaneous cold-working effect, whereas driven rivets in the present tests are found to be no stronger before aging than undeformed wire. Almost all of the previous data on this point have been hardness measurements. Schmid and Wassermann (reference 31), however, show tensile-strength curves giving the same value for deformed and undeformed material before aging. Apparently the deformation immediately increases the hardness but not the strength.

2. The initial rate of age-hardening is supposed to be increased by deformation immediately after quenching, whereas the present data indicate a decrease in the initial hardening rate accompanied by suppression of the incubation period. The suppression of the incubation period seems to be the important effect which accounts for deformed material being stronger than undeformed in the early stages of aging.

3. Material deformed immediately after quenching is supposed to reach its final strength value earlier than undeformed material, whereas the present data show the reverse to be true. The aging curve for driven rivets, however, shows a tendency to a double rise, a nearly stationary value obtaining for aging times of about 1 day to 3 weeks. Previous investigations on strength of driven rivets (references 34 and 35) have not been carried to long enough aging times to show the additional increase of some 8 percent occurring after 3 weeks aging. Furthermore, the present data may not be strictly comparable with previous results in which the effects of small deformations have been observed on stretched or rolled rather than upset material.

ALLOY A17S

The shearing strengths for alloy A17S of undeformed wire and of rivets driven after aging reached their final values after about 8 months aging time, while the aging of rivets driven before aging was not completed before 2½ years aging time. The deformation of rivet driving produced a small increase in shearing strength (about 5 percent) immediately after quenching, but driving rivets that had been aged from 20 minutes to 4 hours in the undeformed condition weakened them slightly. For aging times of more than 4 hours, the immediate increase in strength on driving rose; for material aged 2 weeks or more, it was about 6 percent and practically constant. Rivets driven immediately (less than 5 min.) after quenching aged more slowly than undeformed wire at all times, and it is doubtful whether the eventual strength (after 2½ yr. aging), 11 percent less than the final strength of undeformed wire, represented the final strength of rivets driven before aging. No data were obtained on the aging after driving of rivets driven more than 5 minutes after quenching, although such aging undoubtedly occurs.

Aging curves for duralumin-type alloys of less than 3½ percent copper content, similar to A17S, presented by Matthaes (reference 36) and by Hansen and Dreyer (reference 28) are in qualitative agreement with the present data, although not directly comparable. Results obtained by Fraenkel (reference 24), Meissner (reference 25), Teed (reference 22, pp. 23–31, or reference 23), and Irmann (reference 37) on the comparative effects of deformation before and after aging on strength of duralumin-type alloys are also in qualitative agreement with the present data.

ALLOY 53S

The data show that the time required for attainment of final strength of alloy 53S was greater than 2½ years, for either deformed or undeformed specimens. The cold work of rivet driving had no effect on the immediate strength of material aged up to 6 hours; for material aged from 6 hours to 1½ years, the immediate effect was to weaken the material by amounts up to 4 percent; material aged over 1½ years was slightly strengthened by such deformation. No data were taken on the aging after driving of rivets that had been aged before driving, but the results of Kientz and Hartmann (reference 38) show that, for a given total aging time after quenching, the strongest rivet is always the one for which the least amount of the aging occurred after driving. This result agrees with the present data on aging of rivets driven before aging, the strength of which was always much less (by amounts up to 22 percent) than that of undeformed wire aged for the same length of time. The curve for rivets driven before aging shows a well-marked double rise, the strength being practically constant for aging times from 6 hours to 1 week. This result may be responsible for the apparently erroneous conclusion that cold-worked material completes its aging faster than undeformed material (reference 39).

The tests involving precipitation heat treatment of 53S alloy (table VII) suggest that a solution heat treatment obliterates the effects of previous operations so that the strength of a specimen depends only on its history subsequent to the last solution heat treatment. The value of 26,100 pounds per square inch given in table VII for the shearing strength of 15 specimens of wire indicates a possible exception to this conclusion. No significant effect on strength could be attributed to room-temperature aging after precipitation heat treatment. Room-temperature aging between the solution and the precipitation heat treatments markedly reduced the strength attainable by the precipitation heat treatment. The data are inadequate to evaluate the relation of this effect to the amount of time between the heat treatments. All the foregoing results are in qualitative agreement with the conclusions of Brenner and Kostron (reference 39) concerning German alloys of the magnesium-silicide type.

CONCLUSIONS

The ratio of shearing strength to tensile strength of undeformed wire remained constant, for each alloy tested, independent of aging time at room temperature. This ratio varied from 0.60 to 0.70 and the higher the tensile strength the lower the ratio, in the order: 24S-T, 17S-T, A17S-T, 53S-W. The aging times at room temperature required for undeformed wire of each alloy to reach practically its final value of strength were, approximately: 24S, 7 hours; 17S, 3 days; A17S, 8 months; 53S, more than 2½ years. The strength of 17S material did not begin to increase until after an incubation period of about ½ hour

The aging times at room temperature required for rivets driven before aging to reach practically their final strengths were, approximately: 24S, 3 months; 17S, 1½ years; A17S and 53S, more than 2½ years. Ninety-five percent of their final strength was attained by rivets of alloys 24S and 17S, driven before aging, after approximately 1½ days and 6 weeks' aging time, respectively.

The immediate effect on strength of the cold work involved in driving rivets was sometimes an increase, sometimes a decrease, depending on the alloy and the aging time before driving. The effect on subsequent aging of this cold work was in all cases a retardation, except only that there was no incubation period for 17S rivets driven before aging. Thus, for a given total aging time after quenching, rivets driven after aging were always stronger than those driven before. Data covering considerably longer aging times would be required to determine certainly whether the final strength attained by a rivet driven before aging is less than that of undeformed wire.

The final values of driving stress for A17S and 53S rivets were reached after aging times of approximately 6 months and 1½ years, respectively. The final driving stress for A17S-T rivets was slightly higher than that required for 17S rivets immediately after quenching. The final driving stress for 53S-W rivets was slightly higher than that for A17S rivets immediately after quenching. The high driving stress required for a standard cone-point head on a 24S rivet driven immediately after quenching resulted in frequent crack formation.

Precipitation heat treatment of alloys 53S had to be carried out immediately after quenching to obtain the highest possible strength values. No further aging of this alloy occurred after precipitation heat treatment. The strength of a 53S-T rivet after precipitation heat treatment was about the same as that of a 17S rivet immediately after quenching or of a freshly driven A17S rivet driven after aging 1 day. The driving stress required for a 53S-T rivet was about the same as for an A17S-T rivet driven after aging 4 or 5 hours.

National Bureau of Standards,
Washington, D. C., *February 7, 1941*.

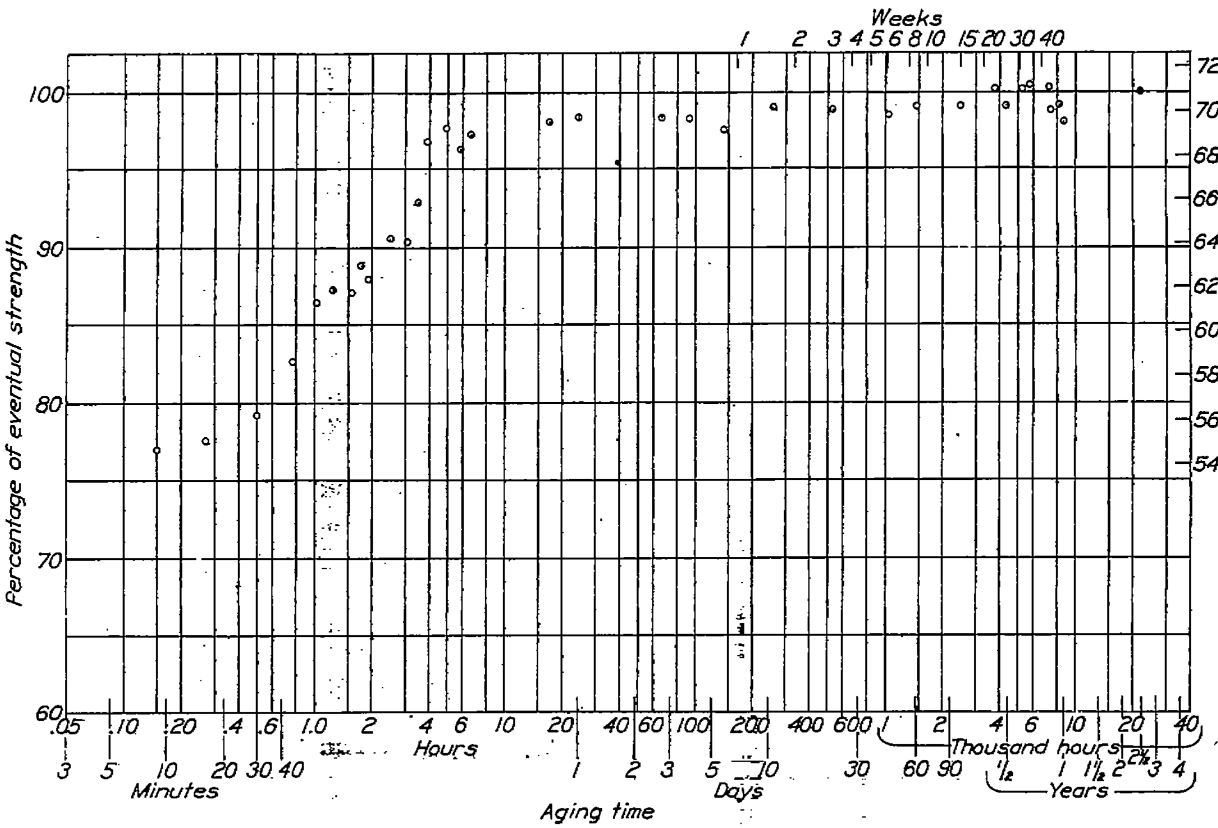

FIGURE 1.—Tensile strength of rivet wire, alloy 24S.

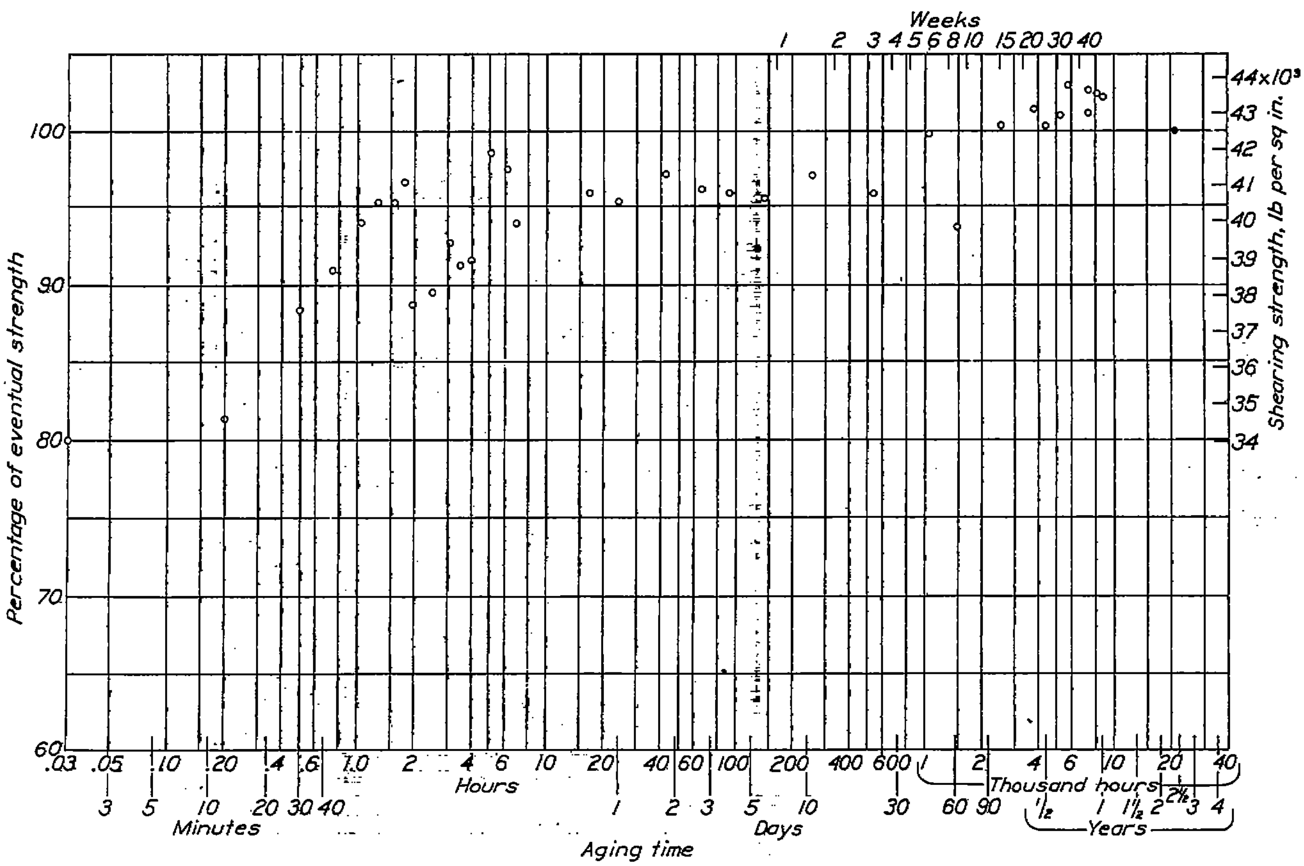

FIGURE 2.—Shearing strength of rivet wire, alloy 24S.

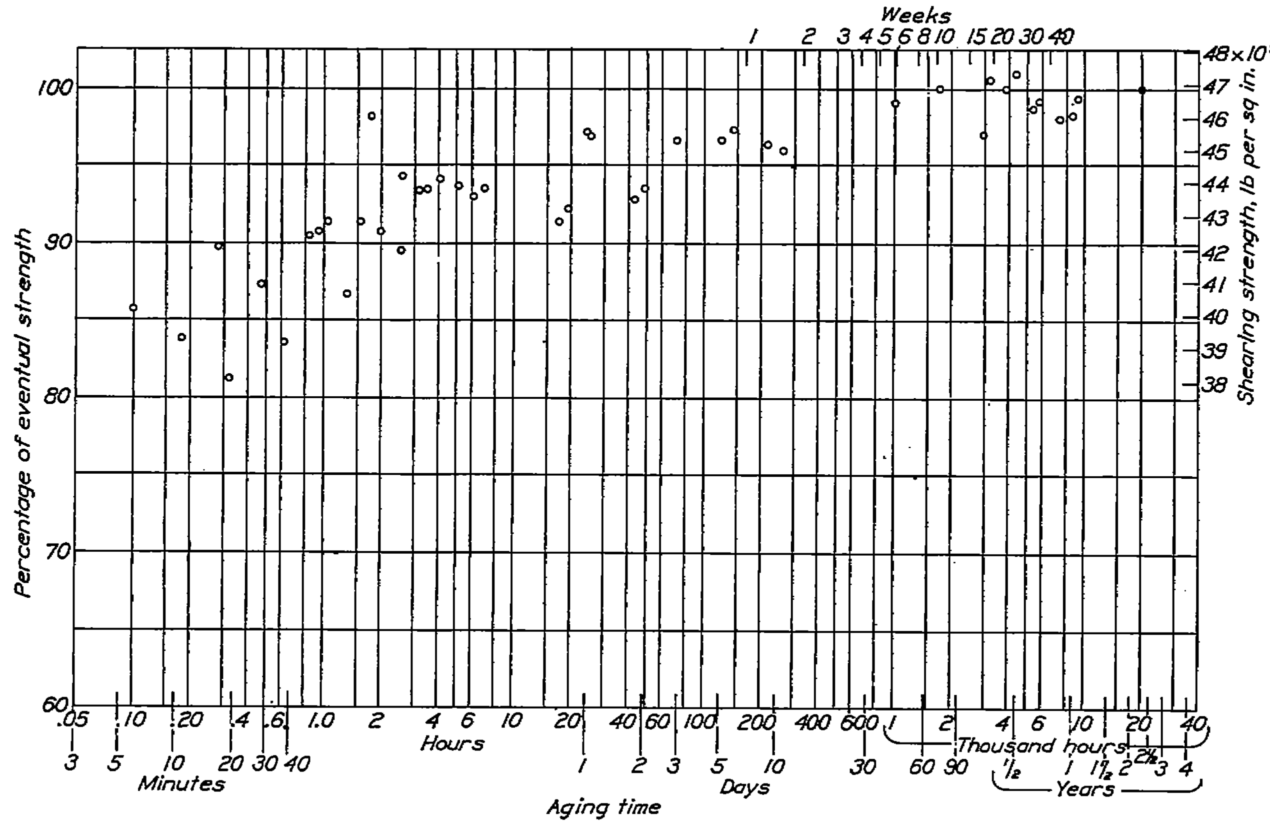

FIGURE 3.—Shearing strength of driven rivets, alloy 24S.

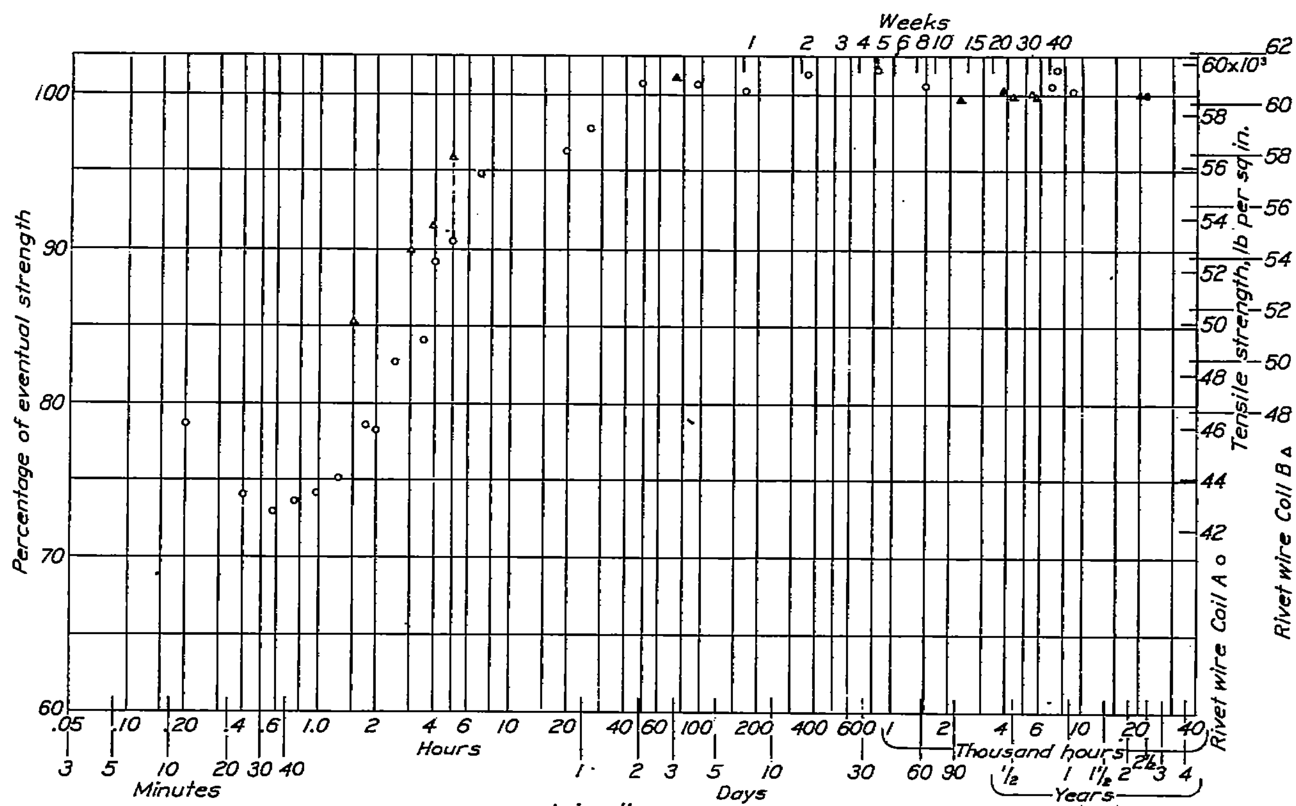

FIGURE 4.—Tensile strength of rivet wire, alloy 17S.

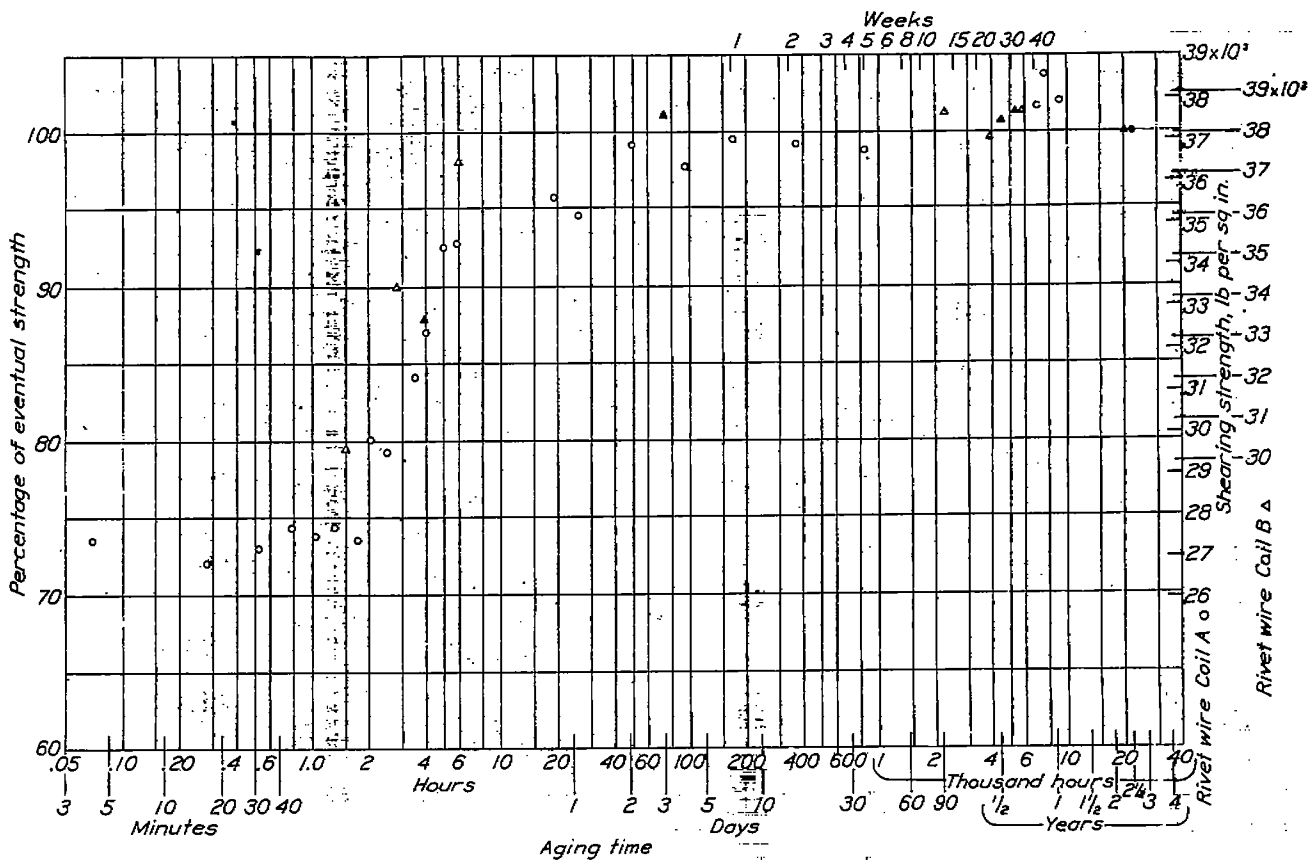

FIGURE 5.—Shearing strength of rivet wire, alloy 17S.

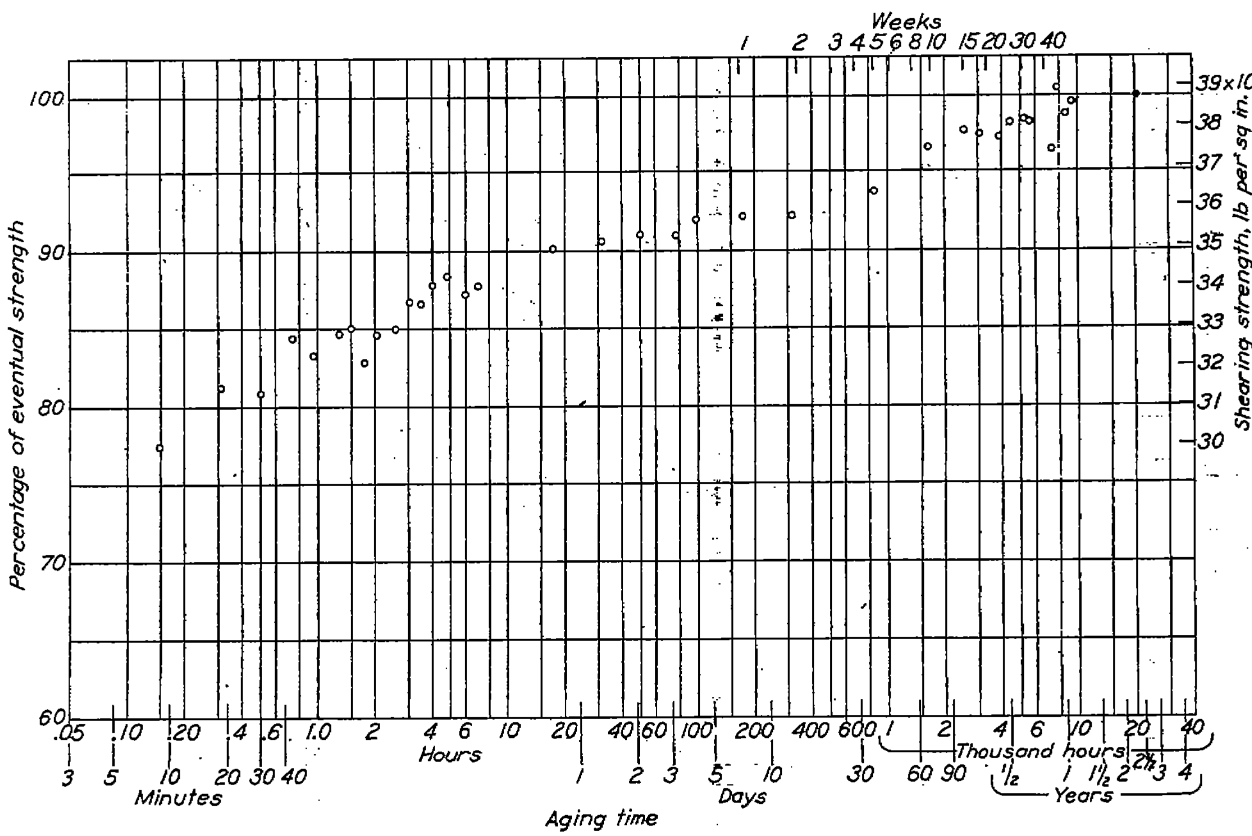

FIGURE 6.—Shearing strength of driven rivets, alloy 17S.

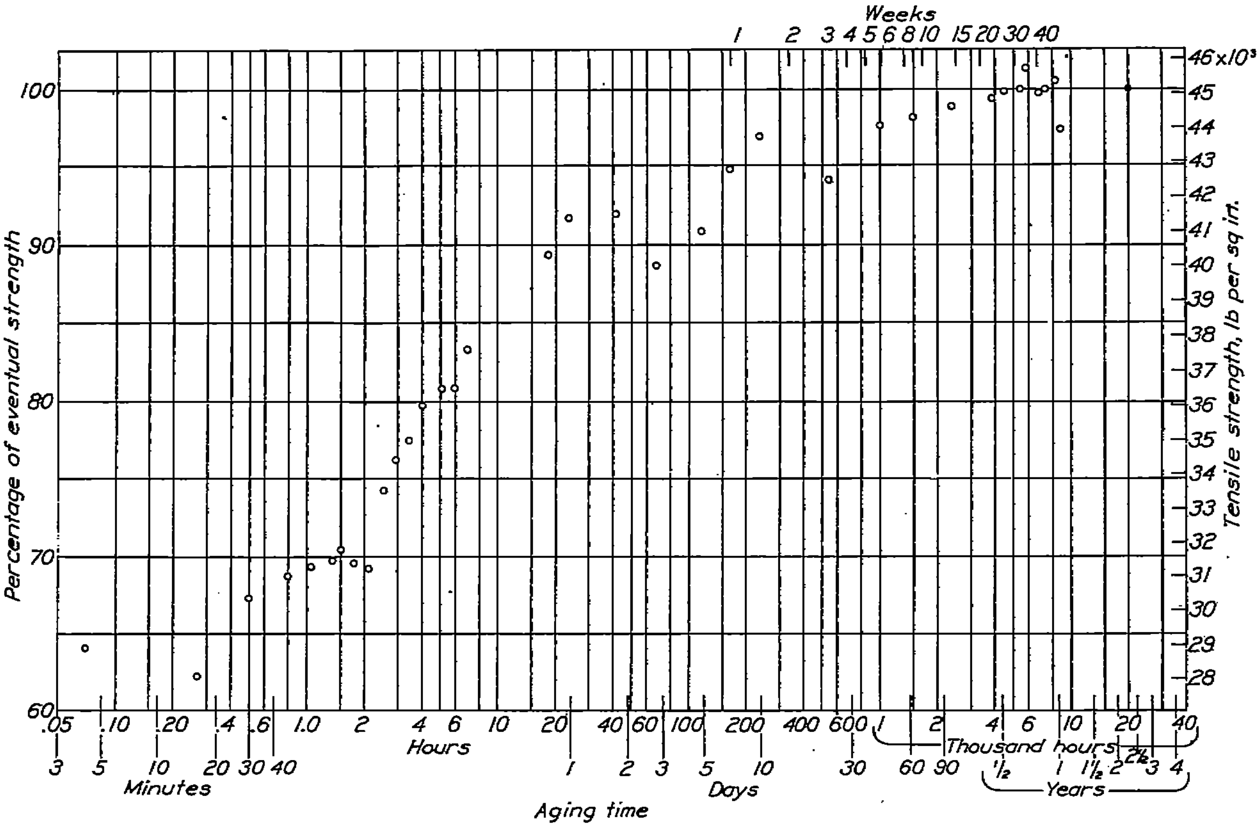

FIGURE 7.—Tensile strength of rivet wire, alloy A17S.

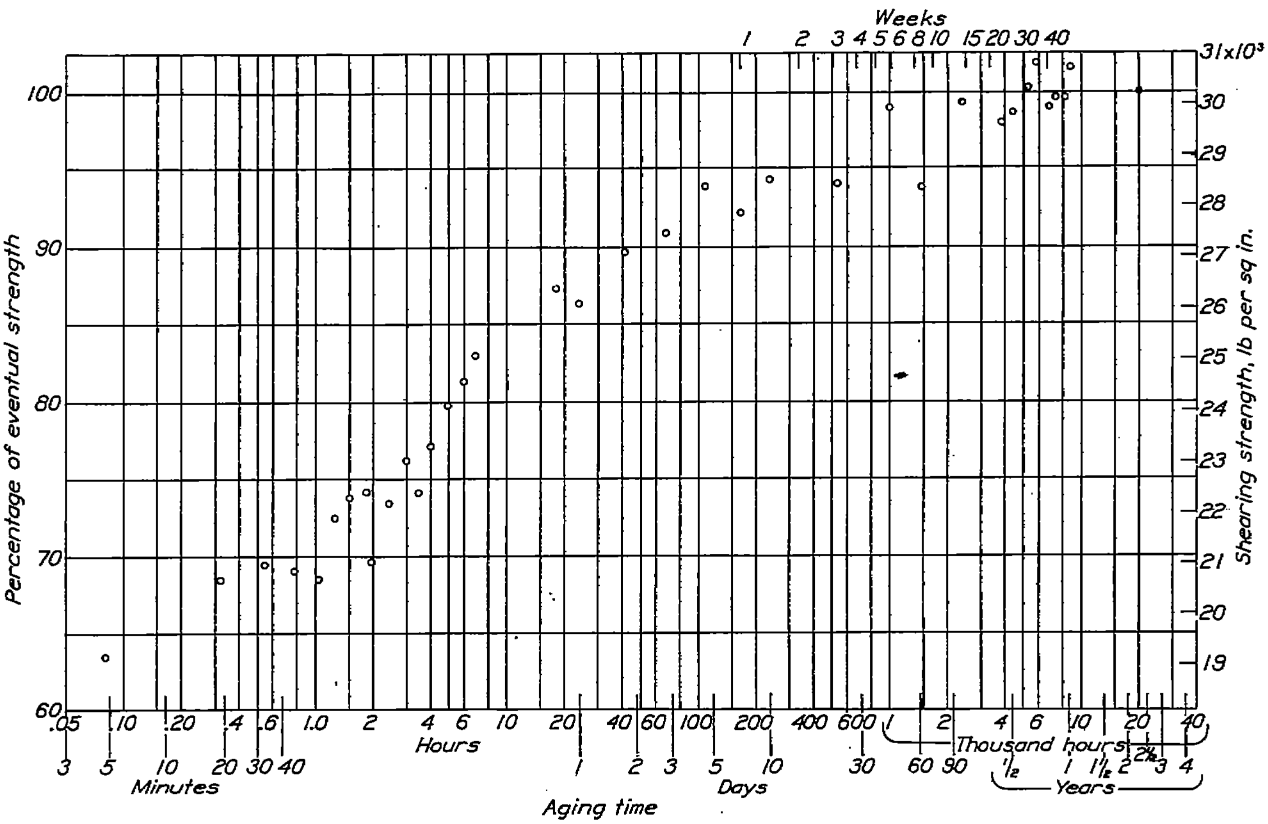

FIGURE 8.—Shearing strength of rivet wire, alloy A17S.

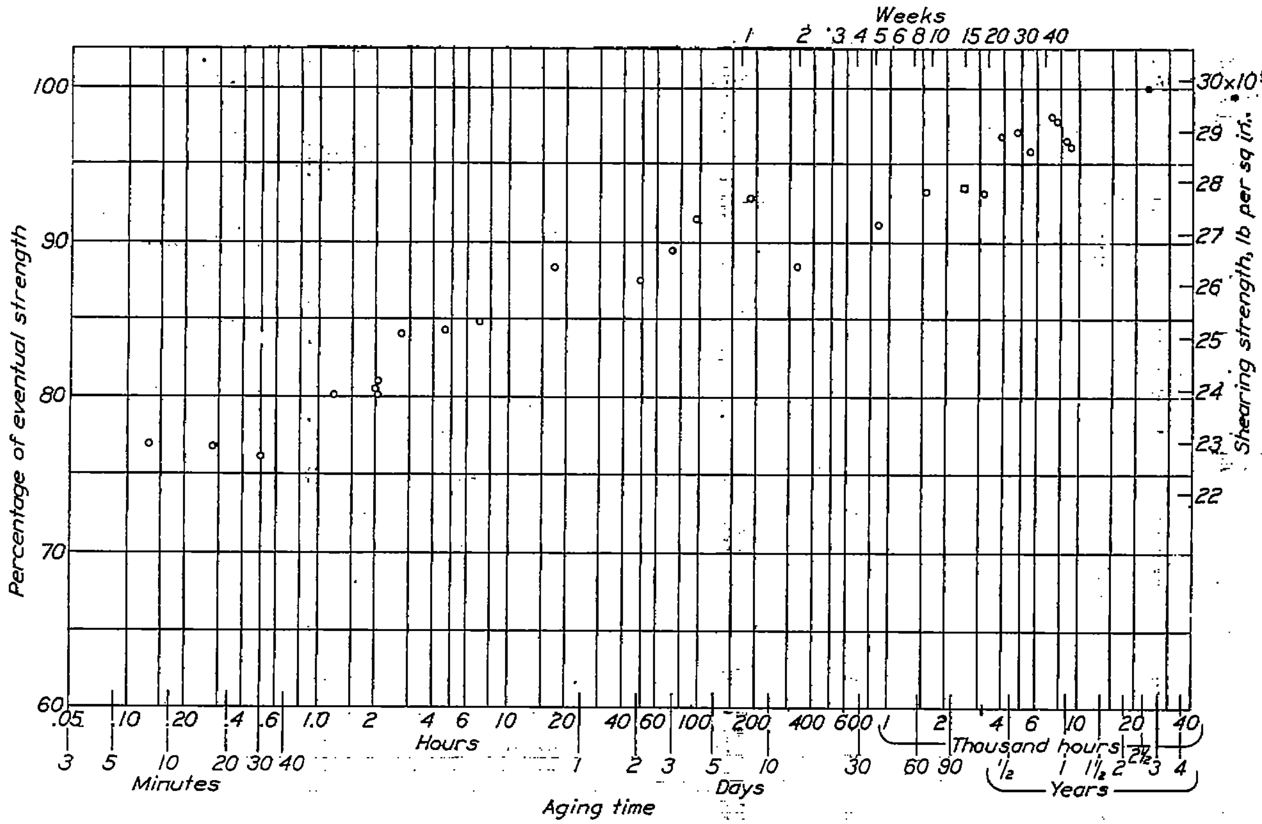

FIGURE 9.—Shearing strength of rivets driven before aging, alloy A17S.

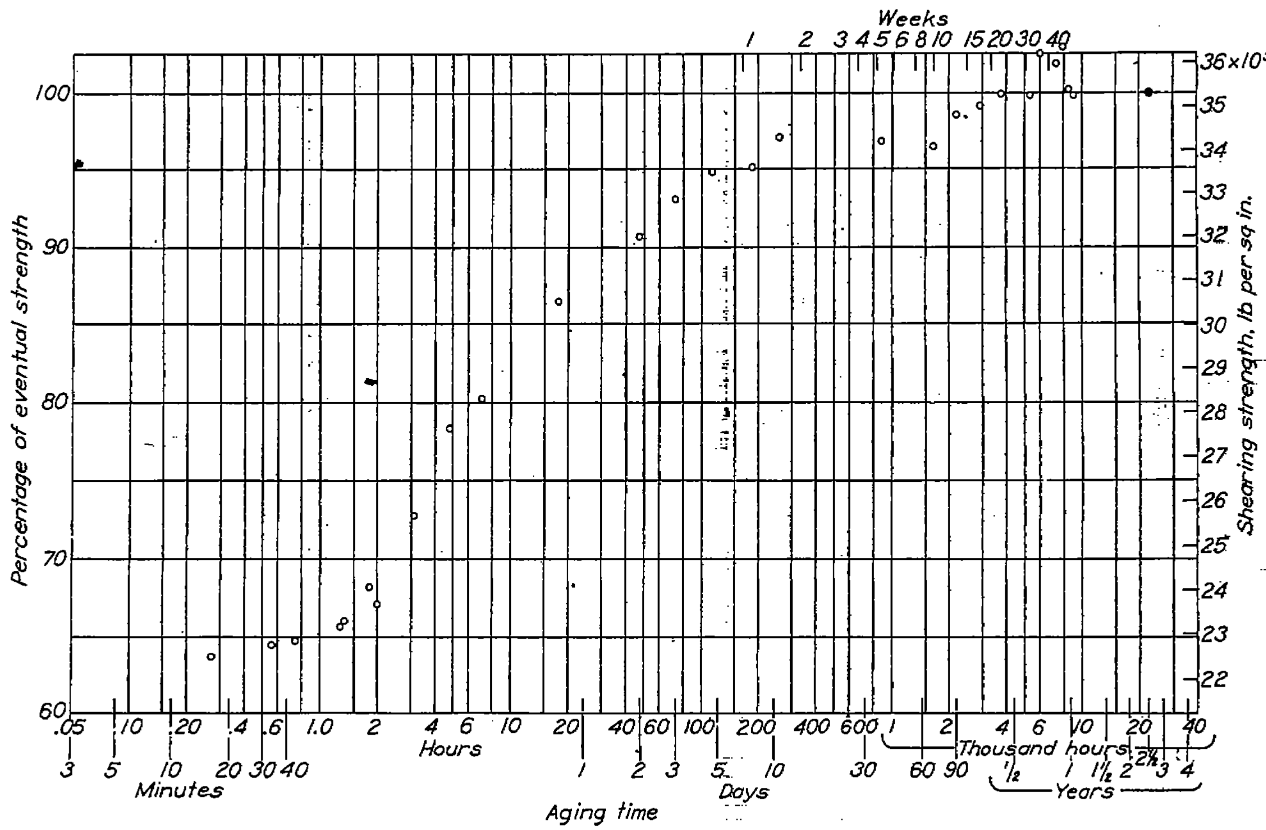

FIGURE 10.—Shearing strength of rivets driven after aging, then tested immediately, alloy A17S

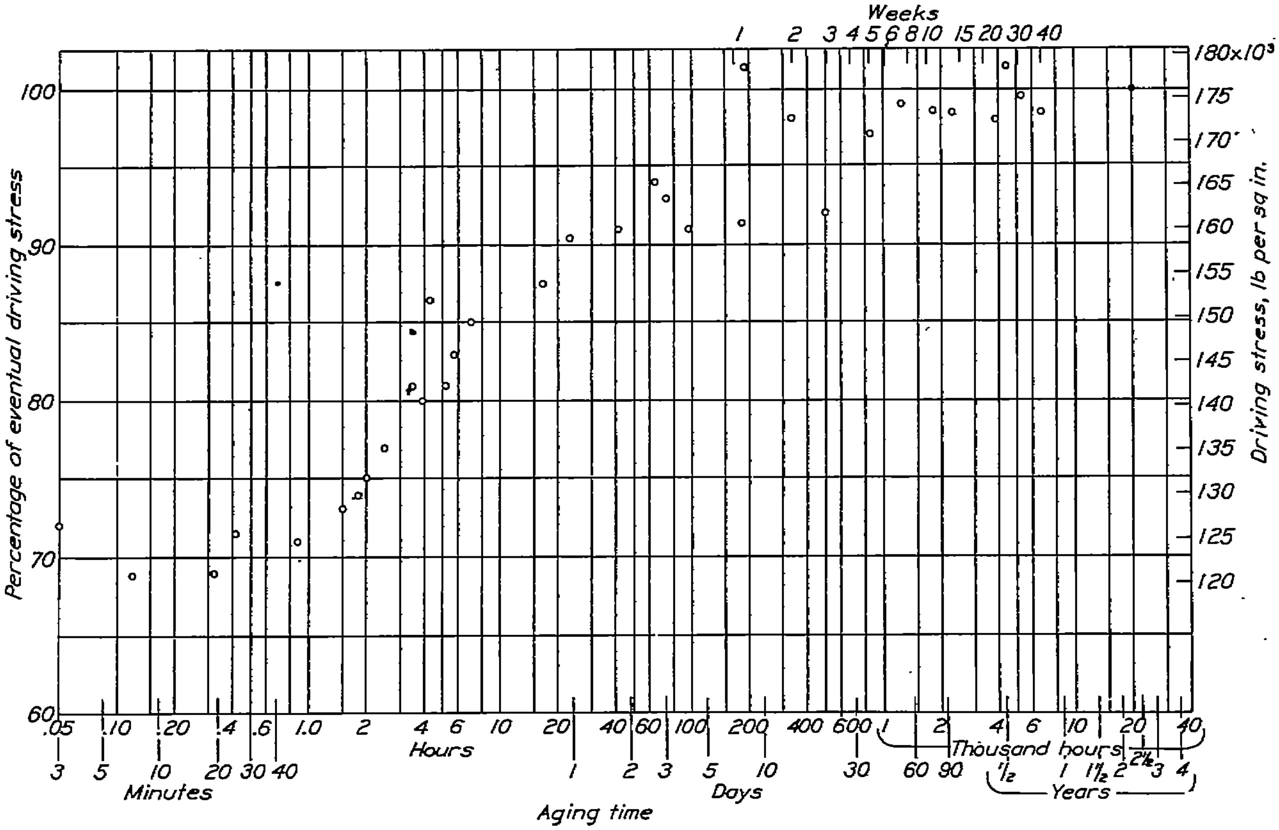

FIGURE 11.—Driving stress for standard cone-point heads, alloy A17S.

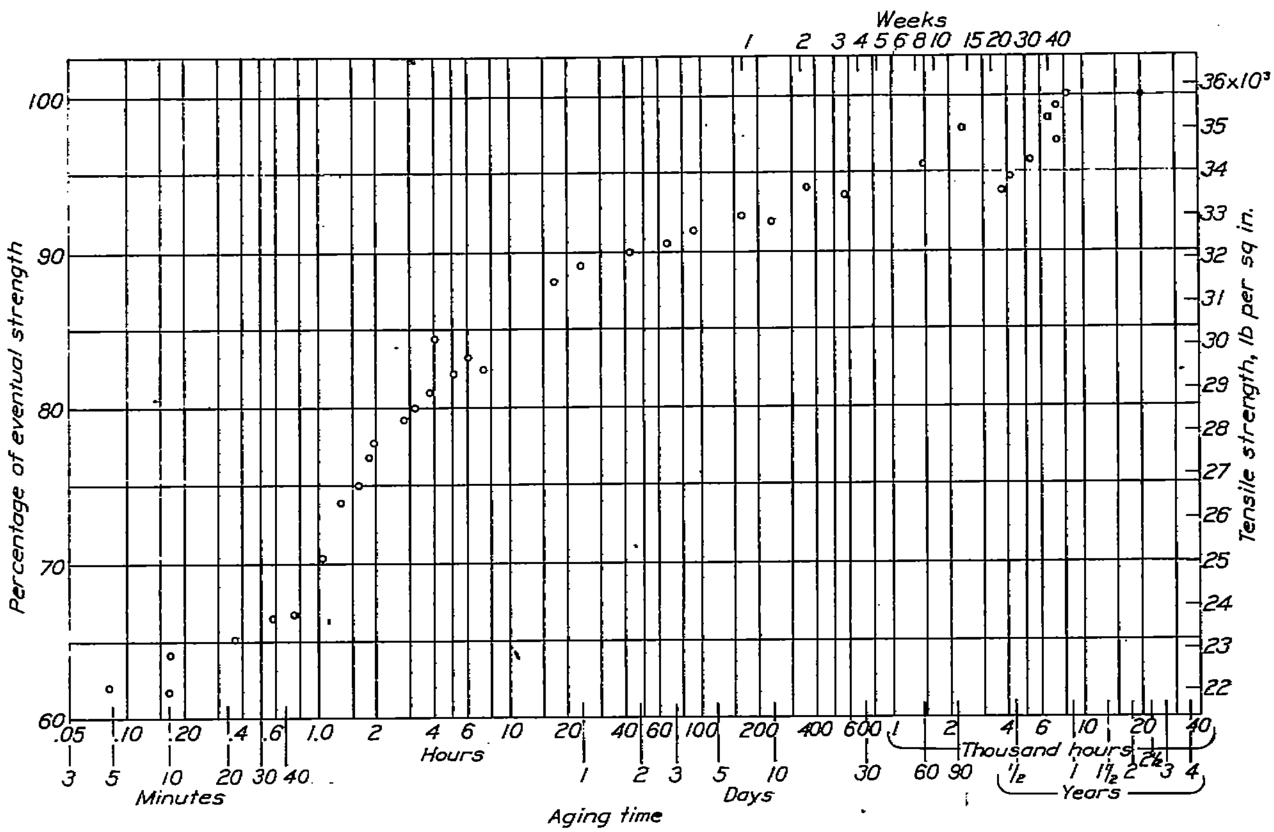

FIGURE 12.—Tensile strength of rivet wire, alloy 53S.

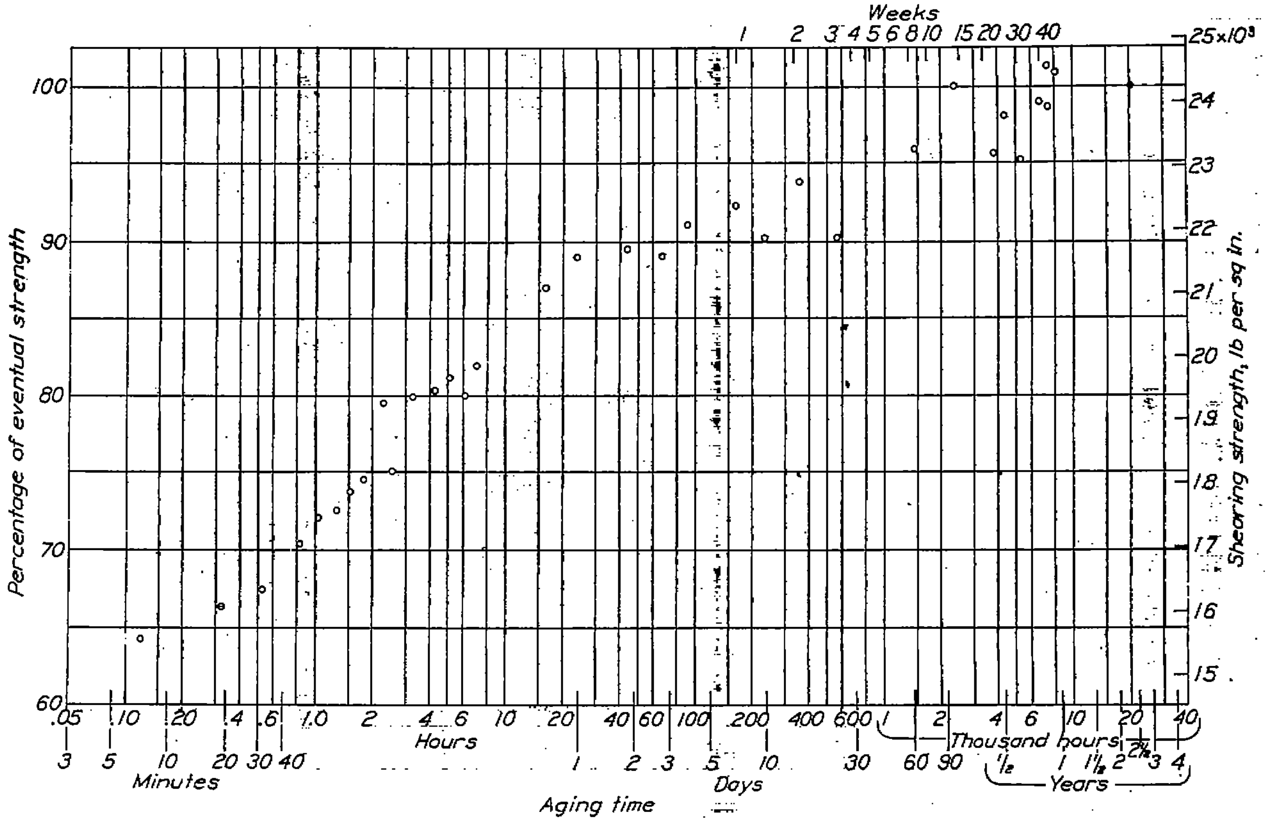

FIGURE 13.– Shearing strength of rivet wire, alloy 53S.

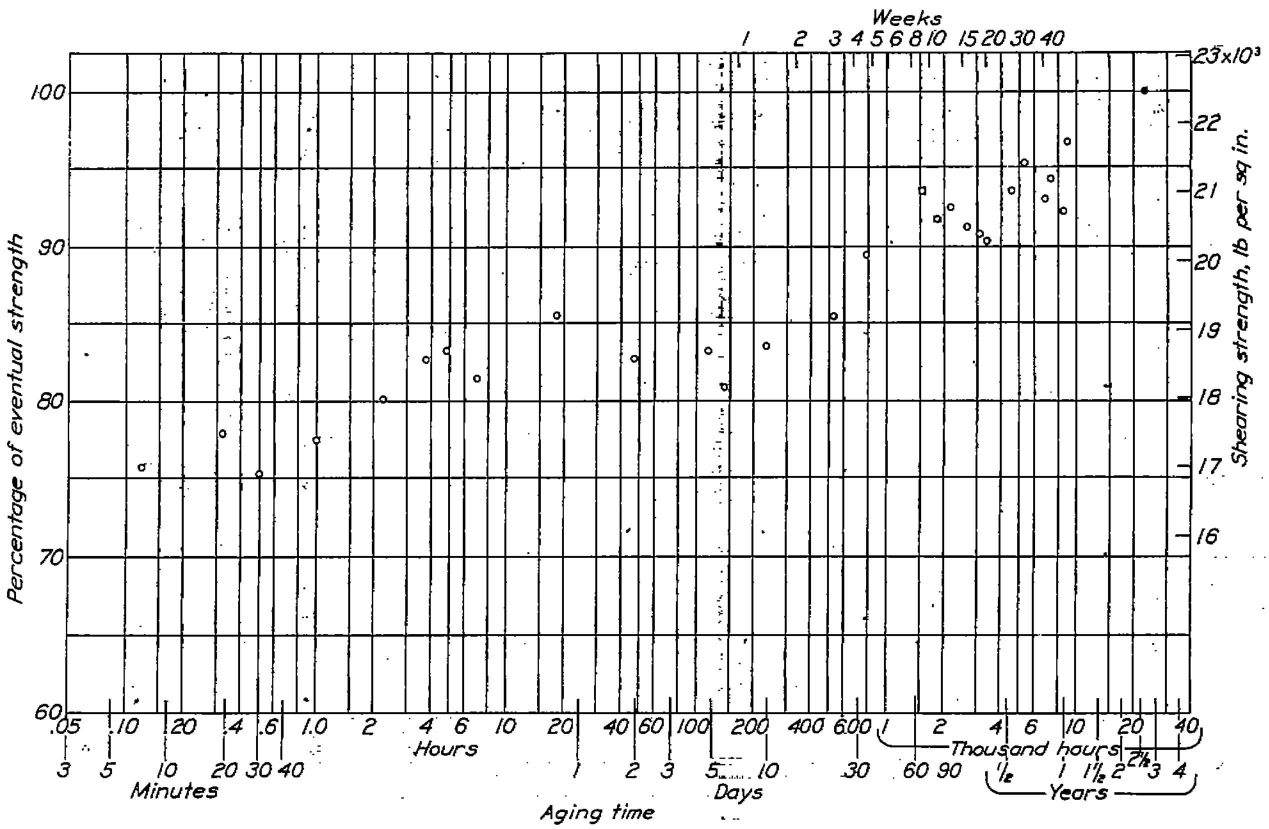

FIGURE 14.—Shearing strength of rivets driven before aging, alloy 53S.

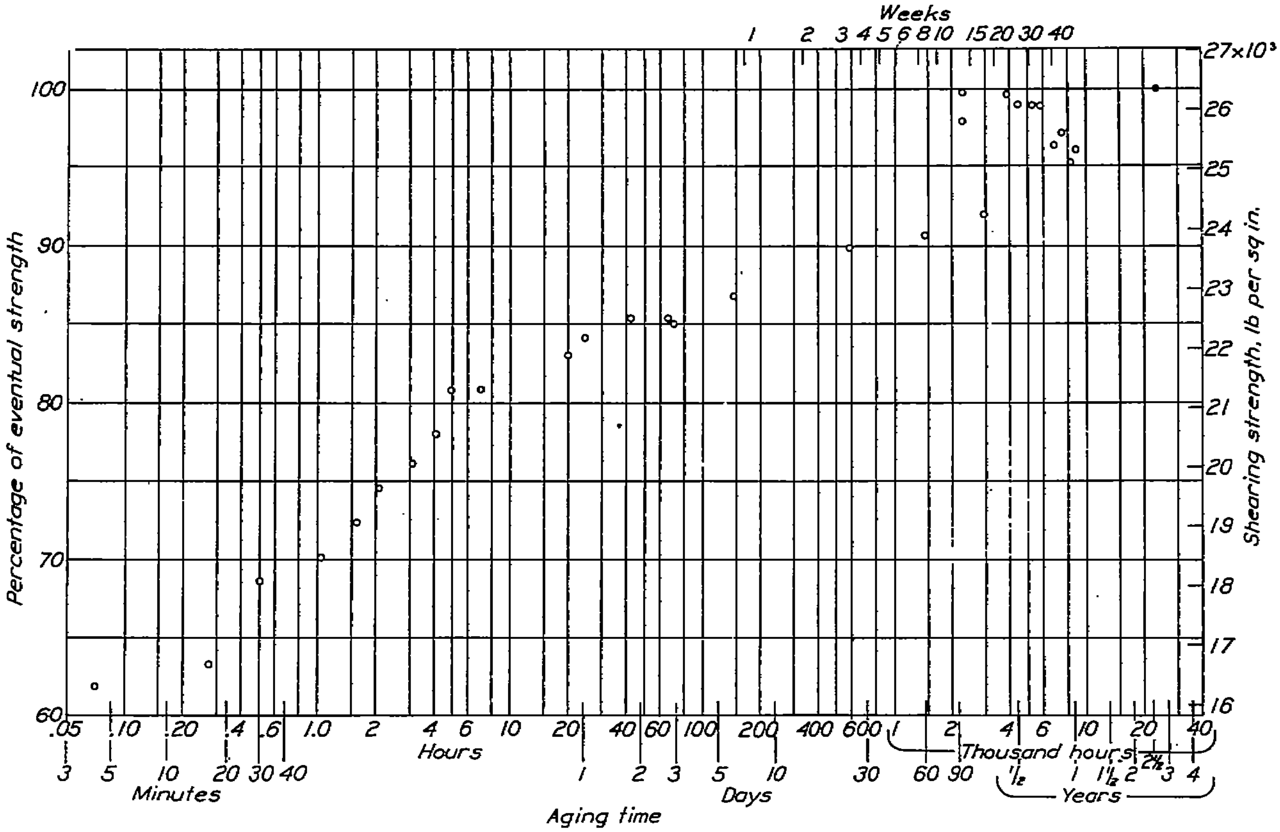

FIGURE 15.—Shearing strength of rivets driven after aging, then tested immediately, alloy 53S.

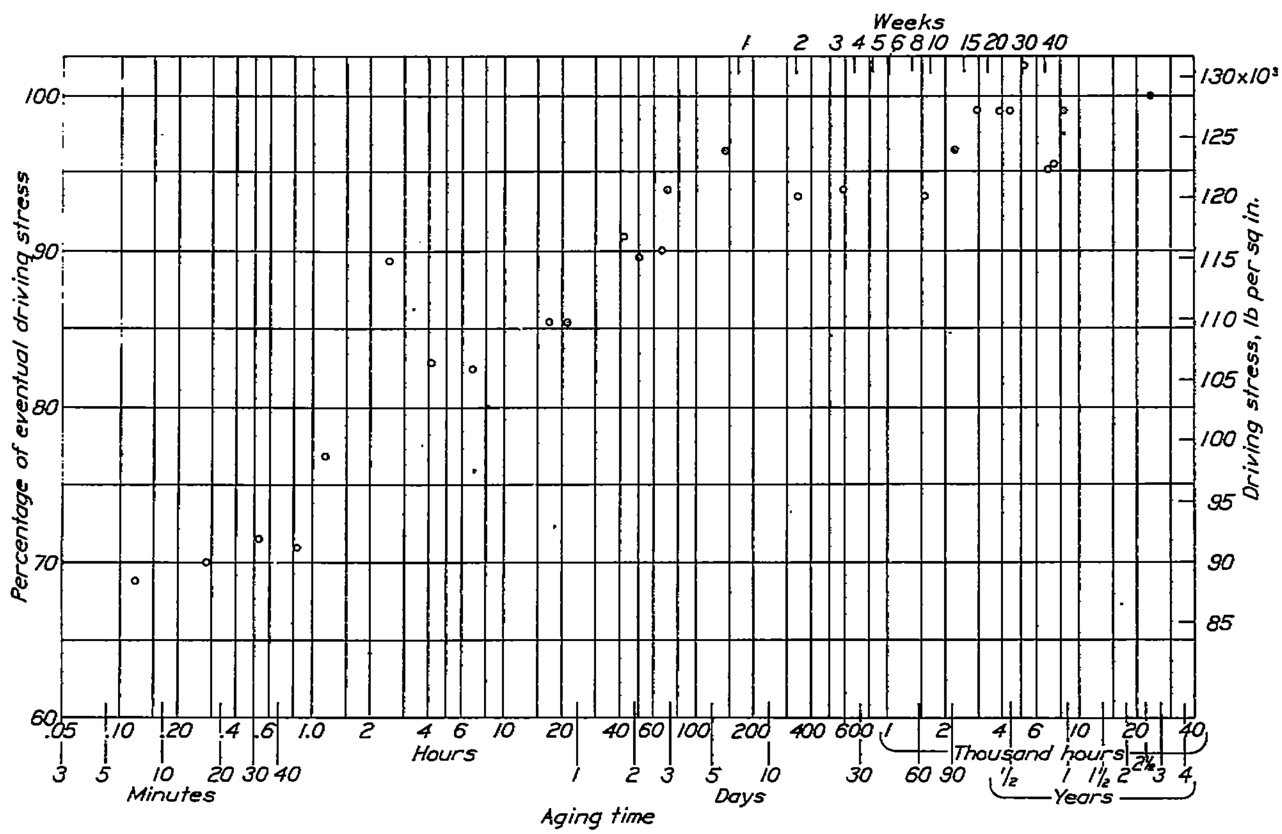

FIGURE 16.—Driving stress for standard cone-point heads, alloy 53S.

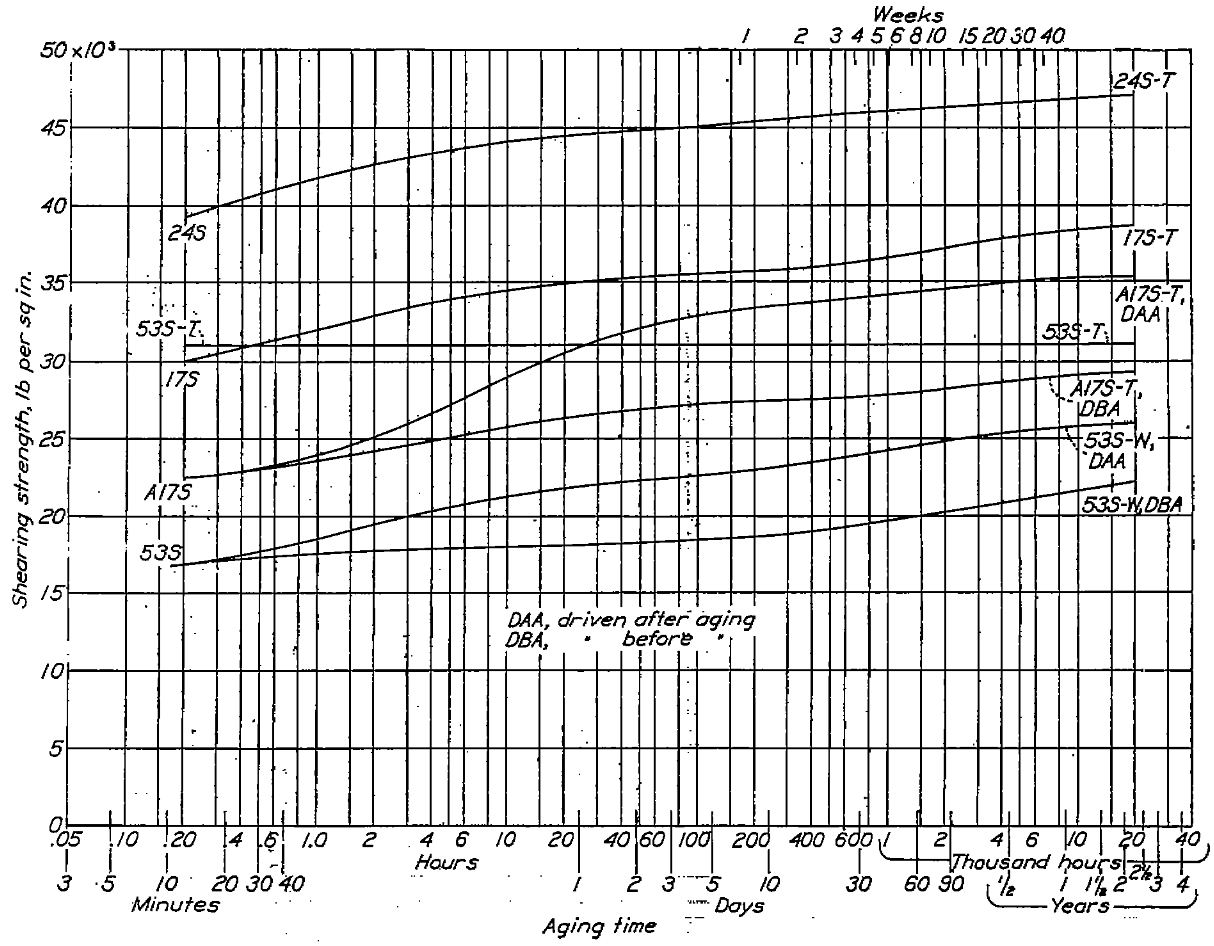

FIGURE 17.—Shearing strength of riveted joints.

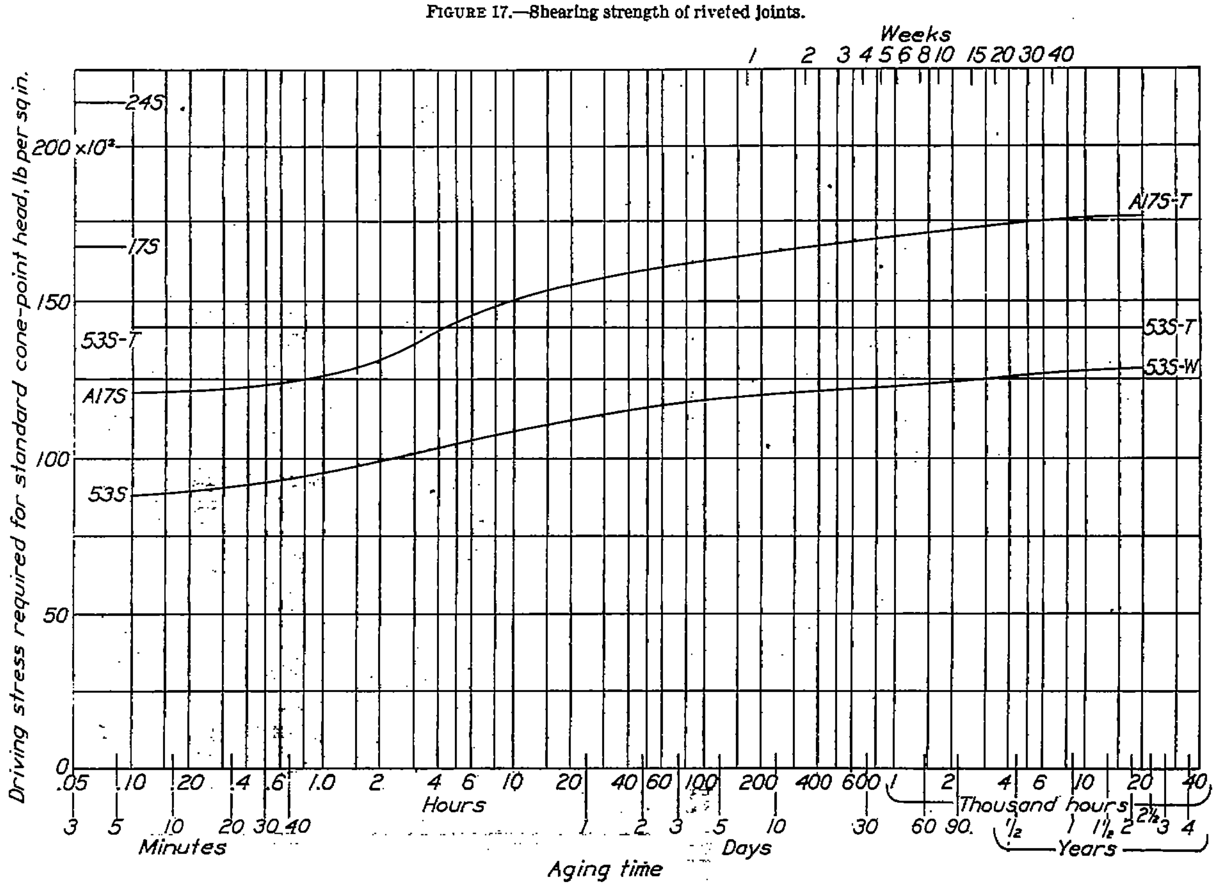

FIGURE 18.—Driving stress for standard cone-point heads.

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